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Testing high-Z QED with SuperEBIT: An estimate of the U^{91+} 1*s* two-loop Lamb shift based on a measurement of the $2s_{1/2}$–$2p_{1/2}$ transition in U^{89+}

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Abstract

Starting from the results of a recent measurement of the $2s_{1/2}$–$2p_{1/2}$ transition in U^{89+} made on the SuperEBIT electron beam ion trap, which provided a determination of the 2*s* two-loop QED contribution, we estimate 1.27 ± 0.45 eV for the two-loop contribution to the 1*s* level in U^{91+}. This estimate could be improved by a factor of two or more, if the uncertainties associated with the three-photon exchange in the theoretical calculations were eliminated in the future.

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Keywords: QED; Two-loop Lamb shift; Heavy ion physics; Electron beam ion trap

1. Introduction

Measurements of transitions involving valence electrons in the 1*s*, 2*s*, 3*s*, or 4*s* level, corresponding for example to hydrogen-like, lithium-like, sodium-like, or copper-like ions, provide a window of choice to quantum electrodynamical (QED) effects in high-Z ions. The reason is that *s* electrons sample the fields inside the nucleus more than electrons in any other angular momentum state within a given shell, where such fields are strongest and thus produce the largest QED contributions. The nuclei of the heaviest ions have the strongest fields, and many measurements of the QED contributions have concentrated on the ions of uranium, which is the heaviest naturally occurring element. The QED contributions to the energy of the 1*s*, 2*s*, 3*s*, and 4*s* electronic states of uranium ions in the hydrogen-like, lithium-like, sodium-like, or copper-like charge states or their close-by neighbors are about 267, 48, 8, and 4 eV, respectively, and measurements to determine the contributions involving the *s* electrons in these and neighboring charge states have been made over the past two decades, when sources of highly charged ions became first available. In Fig. 1 we have plotted the accuracy with which QED has been tested by measurements involving high-Z ions with $Z \geqslant 82$. Here the figure of merit used to assess how well the QED contributions are determined is given by the accuracy of the measurement divided by the size of the total QED contributions.

In the past three years, we have made a concerted effort to revisit QED measurements in uranium. We utilized the EBIT-I and SuperEBIT electron beam ions

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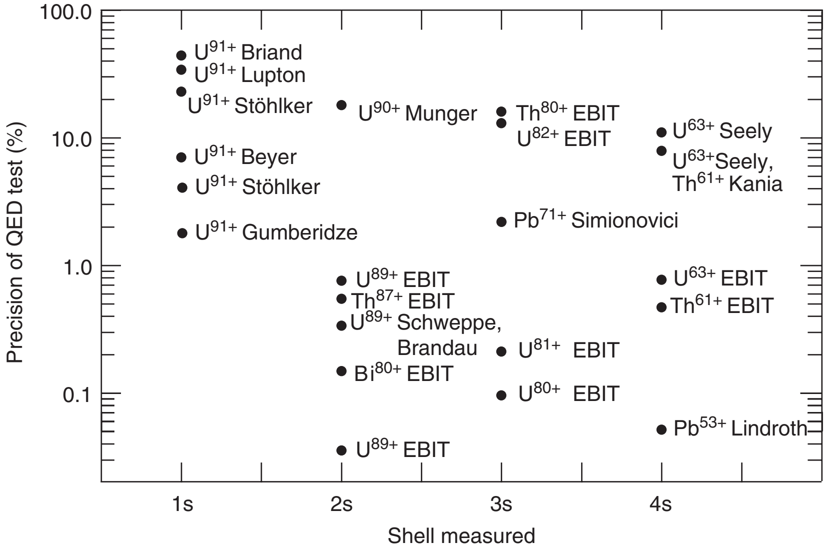

Fig. 1. Overview of the precision achieved in measurements of the QED terms in high-Z ions by studying transitions in different shells. The y-axis shows the experimental accuracy of given measurement divided by the size of the total QED contributions. The 1s measurements are from (Briand et al., 1990; Stöhlker et al., 1993; Lupton et al., 1994; Beyer et al., 1995; Stöhlker et al., 2000; Gumberidze et al., 2005). The 2s measurements are from (Munger and Gould, 1986; Schweppe et al., 1991; Beiersdorfer et al., 1993, 1995, 1998; Brandau et al., 2003; Beiersdorfer et al., 2005). The 3s measurements are from (Beiersdorfer, 1991; Simionovici et al., 1993; Beiersdorfer, 1995; Beiersdorfer et al., 2003). The 4s measurements are from (Seely et al., 1986; Kania et al., 1990; Lindroth et al., 2001; Träbert et al., 2004). Points labeled "EBIT" are from the Livermore electron beam ion trap facility.

traps at Livermore to determine the QED contributions to several of the 4s, 3s, and 2s configurations in various highly charged uranium ions. As shown in Fig. 1, an order of magnitude improvement over previous measurements was achieved in the case of the $4s_{1/2}$–$4p_{3/2}$ transition in copper-like U^{63+} (Träbert et al., 2004). A similar improvement in testing the QED contributions affecting the 3s electron was achieved in a measurement of the $3s_{1/2}$–$3p_{3/2}$ transition in sodium-like U^{81+} and magnesium-like U^{80+} (Beiersdorfer et al., 2003).

Recently, we have measured the energy of the $2s_{1/2}$–$2p_{1/2}$ transition in lithium-like U^{89+} (Beiersdorfer et al., 2005). Our measurement was carried out on the Livermore SuperEBIT electron beam ion trap, and an accuracy of 0.015 eV was achieved. This represents almost a factor of seven improvement over the accuracy achieved by Schweppe et al. (1991), who achieved an accuracy of 0.10 eV, and recently by Brandau et al. (2003), who achieved an accuracy of 0.099 eV. Unlike the earlier, accelerator-based measurements, our measurement employed passive emission spectroscopy. The $2s_{1/2}$–$2p_{1/2}$ transition in lithium-like U^{89+} was recorded with a grating spectrometer specifically developed and tested for this measurement (Beiersdorfer et al., 2004; Schmidt et al., 2004). Following the procedures we used in our other measurements, we used wavelength references provided by low-Z He-like and H-like ions, in particular those of carbon and oxygen.

In the following, we show that the recent measurement of the $2s_{1/2}$–$2p_{1/2}$ transition in lithium-like U^{89+} (Beiersdorfer et al., 2005) can be used to estimate a value for the two-loop contribution to the energy of the 1s electron of U^{91+} within an uncertainty of 0.45 eV. This estimate can be compared to a recent calculation of the two-loop contribution to the energy of the 1s level U^{91+}. It is shown that as theory improves, that same measurement may ultimately provide a test at the 0.22 eV level or better.

2. Results

In our recent measurement of lithium-like U^{89+} (Beiersdorfer et al., 2005) we determined a wavelength of 44.1783 ± 0.0024 Å for the $2s_{1/2}$–$2p_{1/2}$ transition. This corresponds to 280.645 ± 0.015 eV. Our value is in good agreement with the value of 280.59 ± 0.10 eV obtained with Doppler-tuned spectroscopy by Schweppe et al. (1991) on the Bevalac heavy-ion accelerator. However, it is larger than the value of 280.516 ± 0.099 eV inferred by Brandau et al. (2003) from measurements of $1s^2 2p_{1/2} n\ell$ dielectronic resonance peaks on the ESR heavy-ion storage ring, which had to be combined with calculated values of the binding energy of the $n\ell$ Rydberg electron.

As shown in Fig. 1, the recent measurement represents the highest precision achieved in high-field bound-state QED. The roughly 42 eV QED contribution to the $2s_{1/2}$–$2p_{1/2}$ transition in lithium-like U^{89+} was measured with an accuracy of 3.6×10^{-4} or 360 ppm. In fact, this accuracy is more than an order of magnitude better than necessary to determine the two-loop QED contributions.

Rigorous calculations of all two-electron contributions of order α^2 have recently been completed. These include the two-photon exchange term as well as estimates of higher-order photon exchange contributions (Yerokhin et al., 2000; Andreev et al., 2001; Sapirstein and Cheng, 2001). Adding these to the one-photon exchange, first order QED, nuclear recoil, nuclear polarization, and one-electron finite size contributions yields a value for the $2s_{1/2}$–$2p_{1/2}$ transition energy that misses only the two-loop Lamb shift contribution. For example, Yerokhin et al. (2000) calculated a value of 280.44 ± 0.10 eV for the transition energy that misses only the two-loop Lamb shift contribution. The theoretical error limits of this value are dominated by the uncertainty in the nuclear finite size correction to the binding energies and by the uncertainty of the estimate of the three photon exchange contribution. Subtracting the value of Yerokhin et al. from our measured transition energy yields the two-loop Lamb shift of 0.205 eV. Using the theoretical values of Andreev et al. (2001) for the transition energy that excludes the two-loop Lamb shift contribution (280.47 ± 0.07 eV) and of Sapirstein and Cheng (2001) (280.43 ± 0.07 eV) provides additional values of the two-loop Lamb shift. The resulting average value for the two-loop Lamb shift affecting the $2s_{1/2}$–$2p_{1/2}$ transition based on these three theoretical calculations is 0.20 ± 0.07 eV (Beiersdorfer et al., 2005). Other authors have calculated the energy of the $2s_{1/2}$–$2p_{1/2}$ transition in U^{89+} (e.g., Kim et al., 1991; Blundell, 1992). However, these authors do not separate two-loop contributions from their total energy estimate, nor are all one-loop terms rigorously calculated and thus their values cannot be readily used for extracting the two-loop Lamb shift from the measured value.

We can use the derived Lamb shift for the U^{89+} transition to estimate the two-loop Lamb shift of the $1s$ electron in hydrogen-like U^{91+}. To do so, we seek guidance given by one-loop QED calculations.

First, we note that the one-loop Lamb shift of the $2s$ level is about 15% larger than that of the $2s_{1/2}$–$2p_{1/2}$ transition, because the $2p_{1/2}$ level is also affected by QED effects. For example, Blundell (1992) calculated 41.43 eV for the total QED contribution to the $2s_{1/2}$–$2p_{1/2}$ transition, while calculating 47.58 eV for the QED affecting the $2s_{1/2}$ electron in U^{89+}. Second, we note that the U^{91+} $1s$ first-order Lamb shift is about 264.7 eV, as given by Johnson and Soff (1985). This is about 5.6 times larger than that of the U^{89+} $2s$ level calculated by Blundell. Finally, we estimate the U^{91+} $1s$ two-loop Lamb shift by multiplying the 0.20 ± 0.07 eV (Beiersdorfer et al., 2005) inferred two-loop Lamb shift from our recent measurement by -6.39. Here the sign change reflects the fact that the two-loop term in one case affects the total transition energy, and in the other case the level energy. The result is -1.27 ± 0.45 eV. The error limits associated with this result reflect the scaled uncertainty of the theoretical values needed to derive the $2s_{1/2}$–$2p_{1/2}$ two-loop Lamb shift in U^{89+}.

One may think that additional uncertainties with the above result arise from the fact that different authors provide different values for the one-loop QED terms. For example, Indelicato and Desclaux (1990) give 41.10 eV, Blundell (1993) in a subsequent paper gives 41.68 eV, and Chen et al. (1995) give 41.69 eV for the QED contribution to the $2s_{1/2}$–$2p_{1/2}$ transition. The differences are in part due to how the QED contributions (including screening) were obtained in these older results and whether some higher-order terms such as radiative corrections were included. Similarly, the one-loop QED contribution to the $1s$ level in U^{91+} was recently given by Gumberidze to be 266.5 eV (Gumberidze et al., 2005). Here the difference with the value of Johnson and Soff seems to arise because of the use of a different value for the size of the uranium nucleus. Using these different values affects our multiplier used to scale the U^{89+} $2s_{1/2}$–$2p_{1/2}$ two-loop QED term to the U^{91+} $1s$ two-loop QED term by less than 1%. The associated uncertainty (about 0.01 eV) is thus negligible compared to the 0.45 eV uncertainty associated with our estimate, which, as we would like to point out, already includes the uncertainties associated with the finite nuclear size of uranium and the higher-order photon exchange terms.

3. Conclusions

Our estimate of the $1s$ two-loop Lamb shift value (-1.27 ± 0.45 eV) is the first such number based on experimental data. It was derived by assuming that the two-loop terms scale in the same way as the one-loop terms. This assumption, of course, has not been tested, and no additional error has been assigned to this scaling. We can, however, compare our estimate to the $1s$ two-loop Lamb shift value of -1.26 ± 0.33 eV calculated recently by Yerokhin et al. (2003). The agreement is excellent, albeit the agreement is perhaps fortuitous.

Despite the fact that the uncertainty of the $1s$ two-loop Lamb shift estimated from our measurement of U^{89+} by invoking theory is much larger than the experimental uncertainty in the total transition energy, it is still much better than the uncertainties associated with a direct measurement of U^{91+}. This is illustrated in

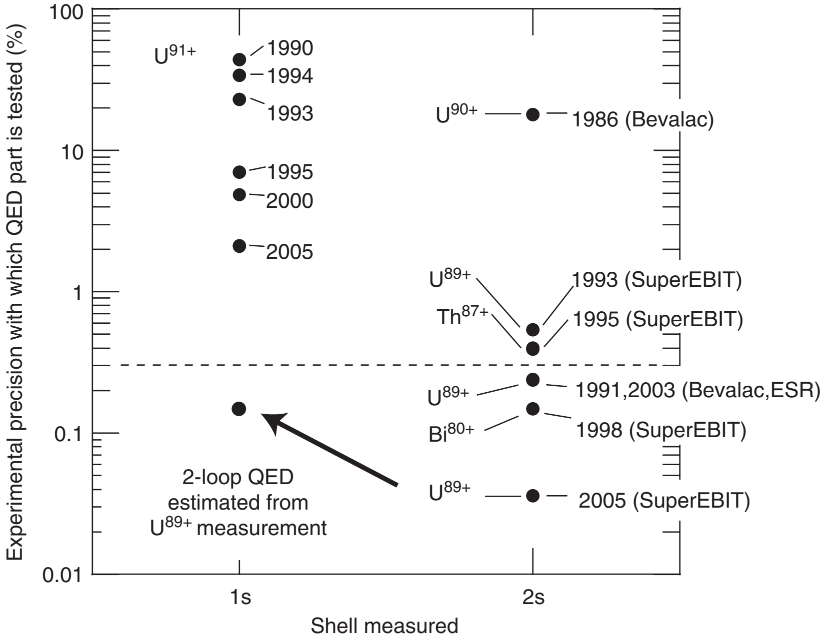

Fig. 2. Precision obtained by estimating the 1*s* QED from the 2*s* QED measurement of U^{89+} relative to direct measurements of the 1*s* and 2*s* QED contributions. The dashed line indicates the measurement accuracy needed to detect to the two-loop Lamb shift in uranium. References for the data points shown with year of publication are given in Fig. 1.

Fig. 2. The best direct measurement of U^{91+} to date reported by Gumberidze et al. (2005) provides an accuracy of 4.6 eV. This accuracy is too low to compare to the 1*s* two-loop Lamb shift value of -1.26 ± 0.33 eV calculated recently by Yerokhin et al. (2003). The uncertainty associated with our estimate is an order of magnitude better than the direct measurement of U^{91+} reported by Gumberidze et al. (2005). The as-of-yet unknown uncertainties in the scaling of the one- and two-loop QED terms used to derive our estimate are not expected to change the overall validity of this comparison.

Theoretical values for the U^{89+} $2s_{1/2}$–$2p_{1/2}$ transition will undoubtedly improve in the near future, especially when the three-photon exchange contributions can be calculated with higher accuracy. In principle, the theoretical calculations are then only limited by the uncertainty of the nuclear size of uranium. It limits the uncertainty of the calculations at the 0.02 eV 1 evel (Yerokhin et al., 1999). This uncertainty is comparable to the uncertainty in our recent measurement (Beiersdorfer et al., 2005). Moreover, the similarity of the scaling for one- and two-loop QED contributions assumed in our estimate will likely be tested by calculations in the near future as well, when an ab initio calculation of the two-loop self energy term in lithium-like uranium will be carried out. After such progress in theory and combining theoretical and experimental uncertainties linearly (quadratically), our recent measurement would test the 1*s* QED contribution at the 0.22 eV (0.16 eV) level. This is 20 (30) times better than the best direct measurement (Gumberidze et al., 2005) of the QED contribution to the 1*s* level in U^{91+} to date.

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